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SYNOPSIS: Water quality monitoring at Cedar Hills Regional Landfill, in King County, Washington has indicated that shallow ground water perched in lodgement till has been impacted by solid waste disposal. A leachate mound to 50 feet in thickness was identified in the refuse which overlies the low permeability till. The leachate head over the till is sufficient to cause downward flow of leachate through the till to shallow ground water, and may contribute to water quality impacts at the site. Lowering the leachate head, therefore, may reduce the potential for impacts on water quality. A study was conducted to obtain estimates of the hydraulic properties of solid waste and to determine if lowering the leachate head using horizontal drains and vertical extraction wells is feasible. This paper discusses the findings of the investigation.

INTRODUCTION

The Cedar Hills Regional Landfill is a 920 acre site in King County, Washington which currently accepts 3,500 tons of refuse per day. It has been operated by King County since 1964. The landfill is located approximately 9 miles southeast of the town of Issaquah (Figure 1). It is situated on the east side of the Puget Sound lowlands, at the foothills of the Cascade Mountains. The Puget Sound lowlands consist of a structural trough between the Cascade Range on the east and the Olympic Mountains to the west. Knowledge of the deep structural geology and pre-glacial history is limited due to over 350 feet of glacial sediments overlying bedrock in the region (Sweet, Edwards and Assoc., Inc., 1984).

The landfill is underlain by Vashon till and undifferentiated pre-Vashon glacial sediments (Livingston, 1971; Rosengreen, 1965; and Vine, 1962). Vashon till was deposited in the Puget Sound region roughly 13,500 years ago during the final stage of the Fraser Glaciation. Glacial deposits identified at the site include up to 70 feet of lodgement till of Vashon age, underlain by over 300 feet of advance outwash sands and gravels deposited during the advance of the Fraser ice sheet and younger ice-contact deposits.

Several historic solid waste disposal areas exist at the site, but the majority of waste received by the County has been deposited on the Main Hill solid wast pile, denoted in Figure 2. The Main Hill refuse area is over 5,000 feet in length along the north-south axis and it is about 1,600 feet wide (Figure 2). The refuse thickness in the Main Hill diposal area has been found to be over 140 feet near the center, and it directly overlies the low permeability lodgement till.

Monitoring of ground water quality has indicated that shallow ground water perched in the low permeability lodgement till has been impacted by solid waste disposal activities at Cedar Hills.

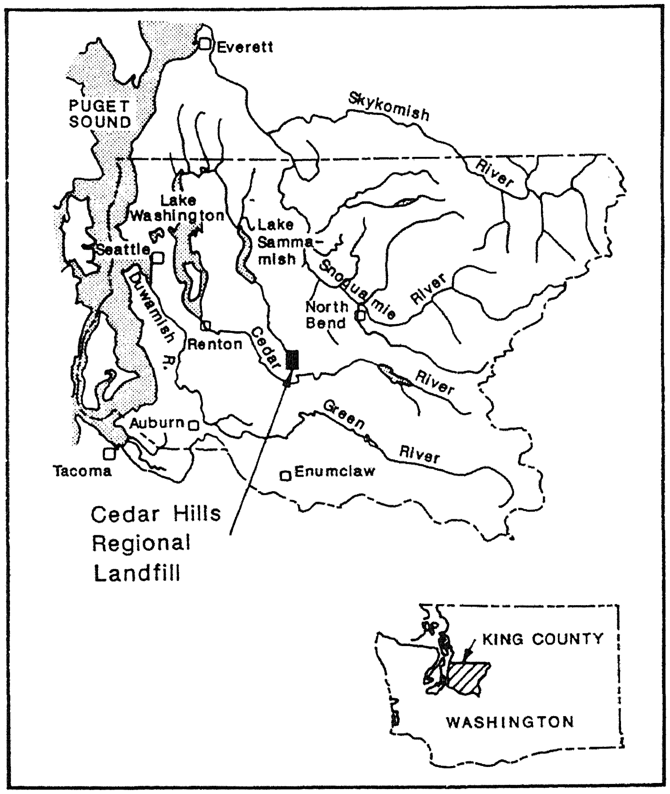

Figure 1. Map of western Washington showing location of Cedar Hills Regional Landfill

Documented leachate seepage on the slopes of the Main Hill refuse area suggested that leachate was mounding in the refuse. The

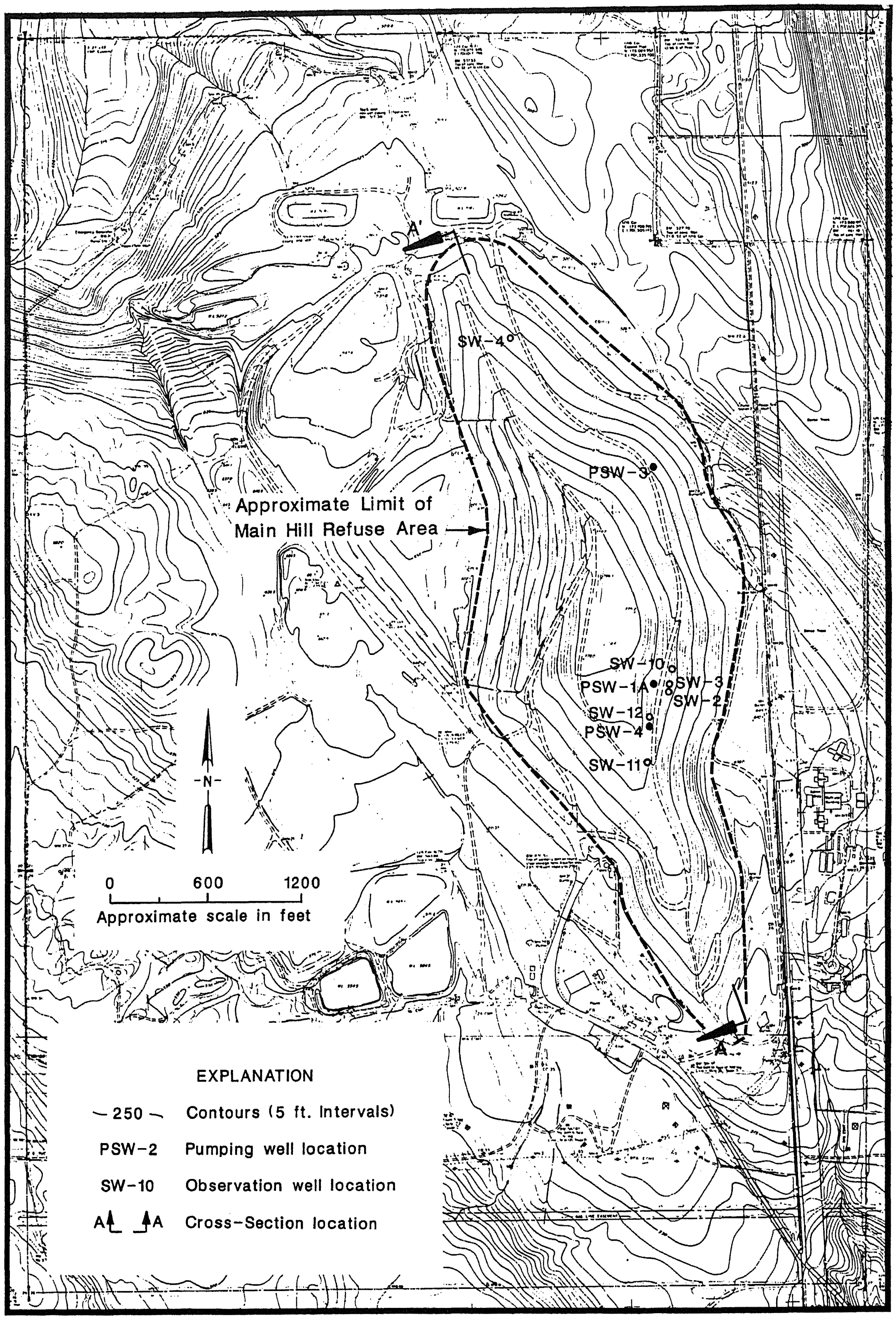

Figure 2. Map of Cedar Hills Regional Landfill

leachate mound over the till may contribute to water quality impacts as a result of percolation through imperfections in the till, particularly if leachate heads are high. If the leachate heads acting on the till can be lowered, the potential for leachate impacts on shallow ground water may be decreased significantly.

PREVIOUS INVESTIGATIONS

In 1985, an investigation was conducted to verify the existence of a leachate mound in the refuse (Sweet, Edwards and Assoc., Inc., 1985). Three borings were advanced through the Main Hill refuse into original ground and 2-inch diameter leachate monitoring wells (SW-2, SW-3, and SW-4, Figure 2) were completed in each boring. A leachate mound, ranging in thickness from 12 feet at SW-4 to 30 feet at SW-2, was identified in all three wells; and landfill gas pressures to 7 psig were measured.

A 4-hour pumping test was conducted on SW-2 to obtain preliminary estimates of the hydraulic characteristics of the saturated refuse. From the pump test data, the hydraulic conductivity was calculated at 3.4×10^{-4} ft/min (1.7×10^{-4} cm/sec), and the storage coefficient was found to be 3.7×10^{-4} suggesting the mound is acting as a partially confined "aquifer" due to the lack of a true confining stratum. The confining conditions are believed attributable to both the compacted layering or "stratification" in the waste as well as high gas pressures which encourage stratification and simulate pressure head (Sweet, Edwards and Assoc., Inc., 1985).

In general, the distribution of the well-compacted or loosely-compacted refuse interlayered with fine- or coarse-grained cover soils was found to be random.

PROJECT OBJECTIVES

In 1987, a comprehensive investigation of the hydraulic properties of the solid waste comprising the Main Hill refuse area was completed to evaluate the feasibility of in-waste leachate head reduction using horizontal drains and vertical extraction wells.

FIELD INVESTIGATIONS

For the feasibility study, three 6-inch diameter wells (PSW-1A, PSW-3, and PSW-4, Figure 2) and three additional 2-inch diameter wells (SW-10, SW-11, and SW-12) were completed in the Main Hill refuse. The wells were installed to conduct long duration pump tests in the saturated refuse and verify previously calculated hydraulic parameters of the solid waste. These data are required to determine the performance of horizontal drains and vertical extraction wells for remedial in-waste leachate head reduction.

LEACHATE MOUND MORPHOLOGY

Monitoring of leachate levels and landfill gas prior to testing indicated that the leachate mound thickness varies areally and fluctuates daily. At PSW-1A (Figure 2), the leachate thickness varied from 45 to 50 feet. During the same period, the leachate thickness in SW-12 varied from 5 to 11.7 feet. Gas pressures also fluctuated daily at some locations. For example, gas pressures measured in PSW-1A varied from 5 to 11 psig during the initial monitoring period, while the pressure in PSW-4 generally remained at 5 psig.

Figure 3 shows the approximate configuration of the leachate mound. Along the north-south axis, the mound is roughly 3,450 feet in length. The extent of the mound along the east-west axis is unknown. The leachate mound is thin toward the north perimeter of the Main Hill and toward SW-11. Several perched leachate production zones were observed during drilling, however the quantity of leachate in these zones appeared small.

PERMEABILITY TESTING

To assess the feasibility of dewatering of the Main Hill refuse area as a remediation option, drawdown and recovery hydraulic conductivity tests were conducted on wells PSW-1A and PSW-4 (Figure 2). Wells SW-2, SW-3, SW-10, SW-11, and PSW-4 were monitored as observation wells while pumping PSW-1A; and SW-2, SW-3, SW-10, SW-12, and PSW-1A were monitored while pumping PSW-4.

Following well installation and development, leachate foam (a mixture of leachate and landfill gas) was observed in the wells and rose up to 75 feet above the static liquid level. In addition, leachate typically blew out of SW-10 about 4 feet above the top of the well casing, and leachate foam blew out of SW-12 about 12 feet above the well casing. As a result of the leachate foam, pressure transducers were required to obtain reliable leachate measurements during testing. Leachate levels were therefore recorded during pumping and recovery periods using a TERRA8 computerized data logger system.

One criterion used to obtain representative leachate levels from each well during drawdown and recovery periods was that constant gas pressures be maintained in each well. To achieve this, pressure-tight well head caps were affixed to each well. The pressure was regulated using a ball valve attached to the well head. On wells PSW-1A and PSW-4, pressure-tight fittings were used for the discharge pipe and electrical and transducers cables. The well head caps on the observation wells included pressure-tight fittings for the transducer cables. In addition, a pressure gauge was attached to a sealed outlet in each well head.

The wells were pumped using an electric submersible pump. Discharge during pumping was regulated using a flow restrictor valve, and pumped leachate was directed to the onsite leachate collection system for treatment and disposal.

Well PSW-1A was pumped for 6-1/2 hours initially at a rate of 2 gpm, but the rate decreased gradually to 0.5 gpm 280 minutes after pumping started. The total observed drawdown was 19.90 feet. No change in leachate level was measured in the observation wells. Prior to testing, the gas pressure in well PSW-1A was measured at 12.5 psig. An effort was

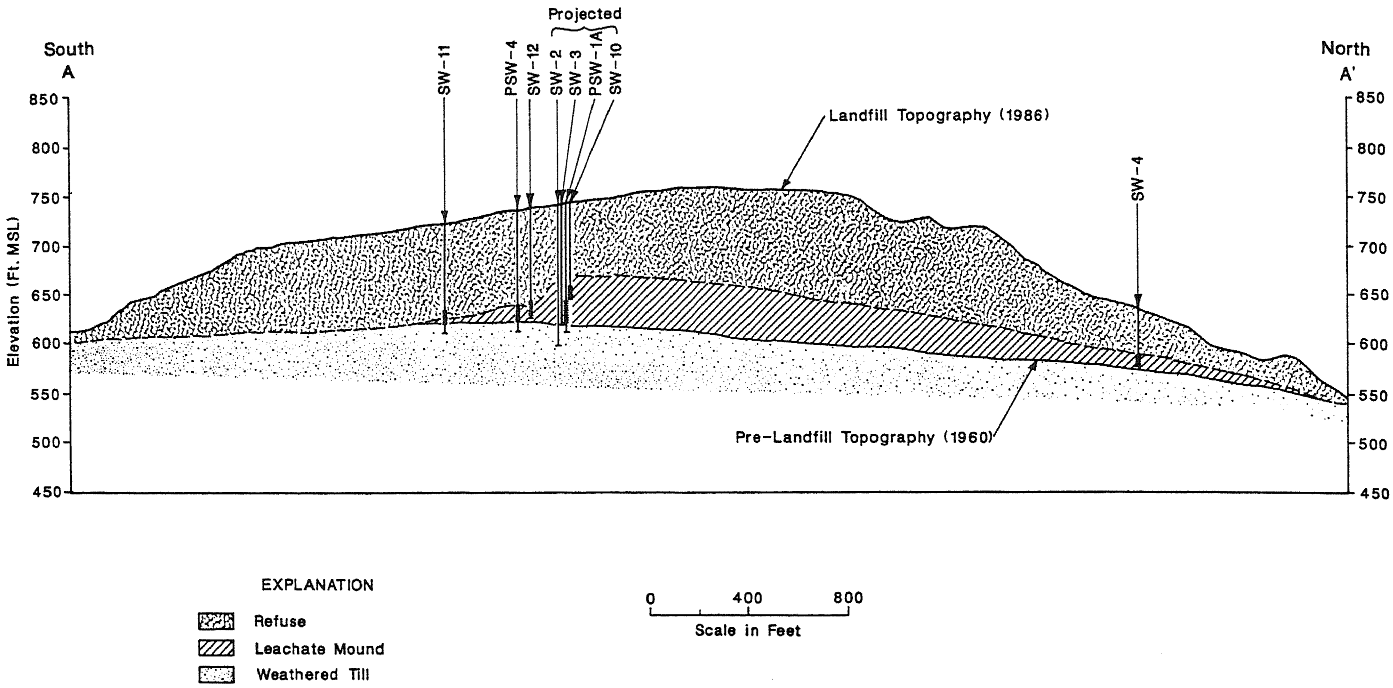

Figure 3. Cross-Section A-A'

made to maintain the gas pressure in all the wells at 2 psig, but roughly 4 hours into the pump test pressures had dissipated to zero at all locations.

Well PSW-4 was pumped for 14 hours at a rate of 2 gpm. During the last hour, the rate decreased to 1 gpm. The total measured drawdown was 4.50 feet. In well SW-12, located 52.8 feet north of PSW-4, 1.96 feet of drawdown was measured.

HYDRAULIC PROPERTIES OF THE LEACHATE MOUND

The hydraulic conductivity and transmissivity of the refuse (summarized in Table 1) were calculated from drawdown and recovery data from wells PSW-1A, PSW-4, and SW-12 using several methods. As noted previously, PSW-1A was pumped at a decreasing discharge rate. The methods used to evaluate drawdown data from this well (Papadopolus-Cooper and Cooper-Jacob, Table 1) account for non-steady state conditions. Methods used to evaluate data from PSW-4 and SW-12 require steady state conditions.

The hydraulic conductivities calculated ranged from 1.6×10^{-3} to 1×10^{-2} ft/min (8.1×10^{-4} to 5.1×10^{-3} cm/sec). The average hydraulic conductivity estimate was 4.7×10^{-3} ft/min (2.4×10^{-3} cm/sec). The storage coefficient was calculated from leachate level measurements made in SW-12, and was found to be 6.9×10^{-4}. These results agree well with the preliminary estimates found during the 1985 investigation.

It is emphasized that the permeabilities found from these pump tests represent horiozontal permeabilities. Vertical permeabilities are expected to be one to two orders of magnitude lower than the reported values.

ANALYSIS OF IN-WASTE LEACHATE HEAD REDUCTION

In general, investigation of the occurrence of leachate in solid waste at Cedar Hills identified a combined liquid head and head due to landfill gas pressures totaling up to 75 feet in the vicinity of PSW-1A, with leachate heads and gas pressures decreasing toward the perimeter of the landfill. The combined liquid head and gas pressure exerted by landfill gas on the upper surface of the till unit may be sufficient to force leachate flow through the till to ground water perched in the low permeability unit. Lowering the leachate head in the refuse pile is expected to reduce the rate of leachate percolation through the till.

For the feasibility study, three scenarios for in-waste leachate head reduction were examined:

1. Horizontal drains,
2. A combined system of horizontal drains and vertical extraction wells,
3. Vertical extraction wells.

The in-waste head reduction analyses are based on achieving a 50 percent head reduction of the leachate mound. For the evaluation, an average leachate head of 29 feet was assumed. A 50 percent reduction of the head, therefore would yield an average head of 14.5 feet and should significantly reduce the potential for impacts on water quality in the vicinity of the landfill. A hydraulic conductivity of 6.0×10^{-3} ft/min was assumed. Additional assumptions include:

- The landfill gas pressure is 0 psig and remains at steady state;
- The refuse is homogenous and isotropic;
- There is constant recharge to the leachate mound;
- The hydraulic properties of leachate are similar to ground water.

Table 1

Summary of Aquifer Parameters for Refuse Using
Several Methods of Data Analysis

Well No	Method used	Transmissivity (gpd/ft)	Hydraulic Conductivity (ft/min)	(cm/sec)	Storage Coefficient
PSW-1A	Papadopulos-Cooper	1069	$5x10^{-3}$	$2.5x10^{-3}$	-
PSW-1A	Cooper-Jacob	377	$1.8x10^{-3}$	$9.1x10^{-4}$	-
PSW-4	Distance-Drawdown	960	$8.9x10^{-3}$	$4.5x10^{-3}$	-
PSW-4	Jacob (Drawdown)	108	$1x10^{-3}$	$5.1x10^{-4}$	-
PSW-4	Jacob (Recovery)	170	$1.6x10^{-3}$	$8.1x10^{-4}$	-
SW-12	Theis	1089	$1x10^{-2}$	$5.1x10^{-3}$	$8.4x10^{-4}$
SW-12	Jacob (Drawdown)	960	$5.3x10^{-3}$	$2.7x10^{-3}$	$4.3x10^{-4}$
SW-12	Jacob (Recovery)	680	$3.8x10^{-3}$	$1.9x10^{-3}$	$7.9x10^{-4}$

The last assumption is particularly important. It is recognized that the hydraulic properties of leachate and water are dissimilar. Consistency, specific gravity, viscosity, temperature, gas saturation, and composition all influence the hydraulic properties of leachate and prevent direct comparison with water.

Horizontal Drain Analysis

The effectiveness of removing leachate from the refuse by a system of horizontal drains was examined using a drain spacing of 475 feet, indicating that 7 drains would be required along the north-south axis of the mound. A graphical relationship between drawdown, drain spacing, aquifer parameters, and dewatering time developed by the U. S. Bureau of Reclamation (USBR, 1978) was used to estimate the time required to lower the leachate head 50 percent. According to this method, a 50 percent reduction of the leachate head by 7 drains can be achieved in approximately 1 month (Sweet, Edwards and Assoc., Inc., 1987).

As a result of drilling limitiations, the length of the drains is expected to range from 200 to 400 feet, with the average length of completed drains being approximately 300 feet. Initial discharge from the system was estimated at 227 gpm, and it is expected to decrease to 76 gpm following 50 percent head reduction.

Several factors may affect the projected performance of horizontal drains in the refuse. The most significant of these include the presence of high landfill gas pressures and the physical characteristics of layered refuse. First, landfill gas pressures up to 12.5 psig may provide sufficient head to increase the rate of leachate flow to the drains, and should effectively improve the drain efficiency. As the leachate mound decreases, however, gas pressures should decrease, as observed locally while pumping well PSW-1A. If the gas pressure exerted of the leachate mound is reduced to 0 psig, the drains are expected to perform within the predicted theoretical efficiencies (Sweet, Edwards and Assoc., Inc., 1987).

Secondly, as previously mentioned, the refuse is interlayered with low permeability cover material and compacted, resulting in "stratification" of the refuse. Hence, it is almost certainly heterogenous and anisotropic to some degree. This anisotropy may impede vertical flow of leachate to drains installed near the base of the landfill, effectively reducing the drain efficiency. A horizontal drain field alone, therefore, may not be sufficient to dewater the refuse.

Combined Horizontal Drain and Vertical Well Analysis

King County has constructed an impermeable liner system as part of active refuse disposal areas on much of the west side of the refuse pile. Eventually the liner will extend to the top of the hill on the west and north sides. Installation of a system of horizontal drains for leachate collection in the waste, therefore, is limited to the south and east side of the waste pile. In addition, the maximum length of successful boring completion will probably be 400 feet. These factors limit the area where horizontal drains can be completed to a small portion of the landfill whose maximum width is about 1,600 feet (Figure 2). Considering these limitations, the performance of a system of horizontal drains for reducing the leachate mound can be enhanced by a network of large-diameter vertical extraction wells.

The number of vertical wells required to supplement the horizontal drainage system was computed by first estimating the total discharge capacity expected to occur from a well field completed in the leachate mound. The following well theory formula (modified from Powers, 1981) was used:

$$Q_T = \frac{7.5 \quad K\ (2Hh_o - h_o^2)}{\ln\ (R/r)} \qquad (1)$$

where; Q_T = Total discharge from the well field

K = Average hydraulic conductivity

H = Average head prior to dewatering

h_o = Average head after dewatering

r = Radius of the entire area to be dewatered with vertical wells

R = Radius of influence

Equation (1) was developed for dewatering analyses for an island where recharge occurs laterally from all points and is modified from the basic well theory formula (Cedergren, 1967):

$$Q_T' = \frac{7.5 \quad K\ (H^2 - h^2)}{\ln\ (R/r)} \qquad (2)$$

which accounts for recharge from a line source. The island calculation was selected for Cedar Hills because it provides a conservative discharge value particularly when the aquifer thickness is unknown or variable.

The radius of influence for the refuse was found to be 238 feet using Sichart's formula (Powers, 1981; TM 5-818-5/NAVFAC P-418/AFM 88-5, 1971, p. 150):

$$R = 3\ (H-h) \quad K \qquad (3)$$

The approximate radius of the portion of the leachate mound to be reduced using vertical wells, r, was calculated at 1241 feet. This value assumes that the mound extends through out the refuse.

From equation (1), the estimated discharge from a system of vertical extraction wells, Q_T, is 508 gpm; and, given an estimated discharge of 76 gpm from 7 horizontal drains completed in the remaining portion of the leachate mound, the total estimated leachate flow from a combined dewatering system is 584 gpm.

Assuming the vertical wells are 24 inches in diameter, the expected yeild is 1.5 gpm per foot of saturation if the hydraulic conductivity is 6×10^{-3} cm/sec. Therefore for an average saturated thickness of 14.5 feet during leachate extraction, the average yeild per well would be 21.8 gpm. From this, 23 vertical wells can theoretically remove leachate from the areas where drains are not completed, and the leachate mound can be reduced to an average thickness of 14.5 feet in less than 5 months.

It is important to note that placement of a final cover over the landfill and the use of an impermeable liner system for current and future development will reduce leachate generation and recharge to the landfill. Decreased leachate generation will enhance the effectiveness of the leachate removal system.

Vertical Extraction Well Analysis

The feasibility of in-waste leachate head reduction using a dewatering system comprised entirely of vertical wells was also evaluated. The parameters for the analysis are identical to those used for the combined system except the radius of the area to be dewatered, r, is increased to the radius of the entire leachate mound, 1,350 feet. The total discharge estimate for a network comprised entirely of vertical wells is 549 gpm. If a yield of 21.8 gpm per well is achievable, 25 wells can theoretically reduce the leachate head to an average of 14.5 feet in approximately 5 months.

CONCLUSIONS

Based on the hydraulic parameters calculated from "aquifer" testing conducted in the saturated refuse, it appears that two alternatives for in-waste leachate head reduction are technically feasible. First, a dewatering system consisting of 7 horizontal drains and 23 large-diameter vertical extraction wells may be able to reduce the average leachate head from 29 feet to 14.5 feet in less than six months, with a total estimated discharge of 584 gpm.

Second, a dewatering system comprised solely of 25 vertical wells is also feasible. From the hydraulic analysis, a system of this design may be capable of reducing the average head 50 percent in approximately 5 months with an estimated discharge of 549 gpm.

The existing leachate collection system has a limited capacity for leachate treatment and disposal which restricts the quantity of leachate that can be removed daily from the Main Hill refuse area. If the horizontal drains are as efficient as predicted by theoretical analysis, it will be necessary to have flow controls on each drain outlet. If flow to the drains is high, risk of blowouts at the slope face is increased when flow from the drains is restricted. Thus potential maintenance problems are associated with completion of horizontal drains. In addition, vertical extraction wells may allow more complete leachate head reduction in the refuse, particularly where the underlying topography is variable. For example, borings for vertical wells can be advanced until native ground is encountered and the well screens can be placed at the till/refuse interface. Less topographic, hence, less complete head reduction, can be achieved when installing horizontal drains. Hence, horizontal analysis of lowering the leachate head in the refuse suggests that the most flexible and effective method for leachate removal is the vertical extraction well system.

ACKNOWLEDGEMENTS

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